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A Quantitative Study of the Combined Effect of Drilling Parameters on Barite Sag in Oil-Based Drilling Fluids

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Abstract

The settling of barite particles in drilling fluids under no-flow conditions and under flow conditions is still a major problem in drilling. The separation of barite particles out of the drilling fluids causes a variety of problems, such as stuck pipe, lost circulation, and poor cement jobs. Furthermore, several severe well control incidents have been caused by barite sag.

This paper presents the quantitatively combined effects of the drilling parameters on dynamic barite sag in oil-based drilling fluids. The drilling parameters include annular velocity, pipe rotation, inclination angle, and eccentricity. Two levels for each parameter were considered to develop the test matrix in this study. For example, the parameter of inclination angle has two levels including concentric drill pipe (e = 0) and eccentric drill pipe (e = 1). The Taguchi method was used to design the test matrix, which greatly reduces the number of experiments required and offers the optimum settings of the control parameters. Based on the two levels of the analyzed parameters, the annular velocity and pipe rotation contribute almost 60% and 21%, respectively, to the prevention of sag. The results also indicate that changing the inclination angle in the range from 60 to 45 degrees from vertical has the least impact on the prevention of barite sag. The results of this study enable drillers and designers to operate and design wells with fewer problems related to barite sag.

Introduction and Literature Overview

In drilling, barite sag is referred as the settling of weighting materials in drilling fluids under flowing (pumping) or no flowing (no pumping) conditions. The term “barite sag” is used because barite is a traditional weight material used in drilling fluids to control the fluid density. While there are substitutes such as manganese tetraoxide, calcium carbonate, and iron titanium oxide, barite is the most widely used weight material because it offers high density with wide availability and favorable economics, and it is environmental friendly.

During drilling operations, the circulation of the drilling fluid needs to stop frequently due to many reasons such as tripping, logging, waiting on materials, severe weather, etc. If severe weather is coming, the well may have to shut down completely for days or weeks and hence the fluid inside the drill-string and inside the annulus is at rest. If the yield stress and the structure of the fluid (thixotropic or gellation property of the drilling fluid) are not high enough, the weighting materials may settle out of the suspension causing a difference in fluid density along the well. The light fluid is on the top and the dense fluid is at the bottom of the well. Because of this separation, the hydrostatic pressure at the open-hole section may be smaller than the formation pressure leading to an invasion of formation fluid into the wellbore.

It is a very common practice that when waiting on materials, drillers normally maintain a low pipe rotation speed to avoid stuck pipe. However, this low rotational speed may cause severe sag because the shear from the pipe rotation breaks the structure of the fluid and hence accelerates the settling of the weighting materials.

During the tripping and logging process (no pipe rotation), there is a low flow of the drilling fluid in the annulus due to the displacement of the fluid by the drill-string. This low annular velocity may also induce barite sag. Several studies have reported that annular velocities close to 30 ft/minute induce barite sag the most.

When circulation is resumed after a period of shutting down the well or after a period of tripping or logging, and assuming sag occurs during no-circulating conditions, the light fluid will come out at the surface first then the dense fluid will come out later. In other words, there will be a fluid density fluctuation during this bottoms-up circulation. The circulating fluid density may vary from very low to very high values in comparison with the designed fluid density. This fluctuation in density will cause changes in the equivalent circulating density (ECD) (and changes in the flowing bottom-hole pressure) leading to many problems such as formation damage, lost circulation, kick, etc. The problem may be more severe with a formation that has narrow operating windows, especially in offshore applications.

Hanson et al. (1990) was one of the first papers demonstrating that barite sag can be traced back to the phenomena discovered by Boycott (1920), who reported that blood corpuscles settle faster in inclined test tubes than in vertical ones. In other words, the settling of solid particles out of suspension in the inclined section is worse than that in the vertical one. This is because the travel distance of the particles to reach to the bottom in the inclined section is much shorter than that in the vertical one. In addition, the sliding (or slumping) of the bed in the inclined section causes the convection currents which drive the lighter fluid up and the bed down, accelerating settling in the suspension zone.

Bern, et al. (2000) studied dynamic sag and also gave the operational guidelines to minimize the sag. The authors realized that: (1) barite sag can be minimized by attention to detail in the areas of well planning, mud properties, and operational practices; (2) barite sag and hole cleaning are related in principle, but are distinguished by their bed characteristics; (3) barite beds are more responsive to removal by mud velocity and pipe rotation than most cutting beds; and (4) barite sag can be exacerbated by low annular velocities, eccentric and stationary drill pipe. The authors introduced a new model to predict barite sag which was found to be an excellent match for a wide range of data (see Problem Statement).

Saasen (2002) pointed out that sag may occur more rapidly in a fluid that has a fragile gel structure. A fragile gel is one that may exhibit high yield strength but after the initial gel breaks, continues to be easily broken. Therefore, the fluid may have relatively high gel strength and still exhibit severe dynamic sag when exposed to a low shear. They also concluded that static sag cannot be predicted from VG-meters. Gel formation is important in avoiding static sag; G'/G'' can indicate sag potential. Dynamic sag can be large even if static sag is low or absent.

Maxey (2006) recognized that oil-based drilling fluid is time-dependent and demonstrates viscoelastic behavior. He focused on elastic modulus G' and viscous modulus G'' by using Oscillatory Rheometry and found that elastic modulus G' may increase and decrease with time. This means the yield structure of the fluid may build up and break down over time. He also concluded that rotational viscometry data is and will continue to be vital to the industry, but provides only limited information as to what occurs rheologically within a fluid. The dynamic evaluation of drilling fluids is increasingly important for understanding the structural behavior of fluids. The evaluation of the viscoelastic structure is broadly applicable for any fluid system and gives a clearer picture of when and why phenomenon such as sag occurs.

Nguyen et al. (Jan 2011) used a flow loop and a modified rotational viscometer by adding the sag shoe to the API-thermal cup to study dynamic barite sag in oil-based drilling fluids. The authors realized that the modified rotational viscometer does not correlate with flow loop sag tests that incorporate pipe rotation, pipe eccentricity, and annular velocity. In other words, the modified rotational viscometer, when used only to measure dynamic sag, provides a conservative estimate of the extent of this phenomenon. The authors also concluded that an eccentric drill pipe induces more sag than a concentric one. However, pipe rotation has a greater impact on the reduction of sag in the eccentric case than in the concentric one.

Nguyen et al. (June 2011) presented the first paper that tried to develop a mathematical model based on the conservation of mass and momentum to predict dynamic barite sag in a pipe flow regime. The authors used the continuum approach to write the momentum equations for solid phase and liquid phase. The numerical solution was required to solve a set of four coupled partial differential equations. The results show the solid concentration in axial and radial directions as a function of time. Then the concentration in the two directions is integrated to obtain the mass accumulation in the test section. The model can predict quite well in the first ten minutes.

Hashemian (2012) applied the particle tracking method called "particle elimination technique" to predict barite sag in annular flow without pipe rotation. The author used the numerical approach to attain the velocity profile. In addition, the falling velocity of a single particle in power law fluid is assigned to the particles. The simulation is divided into two parts: modeling of laminar flow of non-Newtonian fluid in annulus to obtain velocity profile and consideration of the solid particles in the fluid to predict the particle traveling path and time. The author drew several conclusions: (1) annular velocity has a great impact on barite sag; and (2) the numerical simulation shows good agreement with the experimental study on the effects of annular velocity on barite sag in horizontal annulus.

Roy (1990) and Vuchkov et al. (2001) show how to apply the Taguchi method in engineering. This method was developed by Dr. Genichi Taguchi to improve the quality of manufactured goods, and more recently also applied to engineering. Taguchi's work includes three principle contributions to statistics: a specific loss function, the philosophy of off-line quality control, and the innovations in the design of experiments. The last contribution has been widely used in engineering. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation. Therefore, it can also be used to quickly narrow down the scope of a research project thus saving time and resources. In addition, this method for experimental design is straightforward and easy to apply to many engineering situations.

To the best knowledge of the authors, there are no studies in the literature that quantitatively compare the effects of drilling parameters on barite sag. This paper presents the application of the Taguchi method to design the experiments for studying the combined effects of annular velocity, pipe rotation, inclination angle, and eccentricity on barite sag. In addition, a statistical technique, Analysis of Variance (ANOVA), will be used to analyze the experimental data obtained from the Taguchi method. The results of this analysis will help us to quantitatively compare the effects of the drilling parameters on barite sag.

Design of Experiments Based on the Taguchi Method

The ultimate goal of the Taguchi method is to reduce the number of experiments and to obtain a full picture of how the parameters impact the performance parameter value. For example, if one wants to conduct an experiment to fully understand the influence of four different independent variables (four different parameters) – annular velocity, pipe rotation, inclination angle and eccentricity on barite sag (performance parameter value) – and each parameter has three levels (three set values), then the number of experiments based on the factorial design should be $3^4 = 81$. In other words, one has to keep the three parameters constant at one level and change the other parameter three times (three levels). The process is repeated exactly for all parameters by varying the levels of each parameter. In order to see the combined effects of these parameters on barite sag, a statistical technique, such as t-test, needs to be used to analyze the data. However, according to the Taguchi method, an L9 orthogonal array is sufficient to fully understand how these parameters affect the performance parameter (barite sag). The L9 orthogonal array means that there are in total nine experiments to be conducted and each experiment is based on the combination of level values of different parameters.

The objective of this paper is to study the effects of four different parameters on barite sag, namely annular velocity, pipe rotation, inclination angle and eccentricity. Because of the limitations of the testing flow loop, the eccentricity has only two levels: fully concentric and fully eccentric drill pipe. In addition, Taguchi method requires that all the parameters must have the same level. Therefore, the levels of the annular velocity, the pipe rotation, and the inclination angle are also two.

Dye et al. (2006) and Nguyen (January 2011) studied the effect of drilling parameters on dynamic barite sag in a flow loop. The authors agreed that sag can be eliminated if the annular velocity is greater than 100 ft/minute. The authors also pointed out that sag is severe if the annular velocity is less than 30 ft/minute and the inclination angles are 30 – 75 degrees from the vertical. Therefore, this paper will consider two levels for the annular velocities of 16 and 65 ft/minute, the inclination angles of 45 and 60 degrees, and pipe rotations of 0 and 20 RPM.

According to the factorial design, there should be totally $2^4 = 16$ experiments. Each experiment is repeated at least three times so the total number of tests is at least 48. However, if the Taguchi method is applied to design the experiments, the L8 orthogonal array is chosen. In other words, eight experiments are enough to fully understand the combined effects of these four parameters on barite sag. If each test is repeated three times, the total of experiments will be 24 which is 50% less than that of the factorial design. **Table 1** shows the L8 orthogonal array designed based on the Taguchi method. The orthogonal array has the following special properties that reduce the number of tests to be conducted:

- All the levels in each column in the orthogonal array appear an equal number of times. This is called the balancing property of an orthogonal array.
- All the level values of the independent parameters are used to conduct experiments.

Table 1: Orthogonal array L8 – Taguchi Method

Experiment Number	U_{ann} ft/min	ω RPM	e	θ degrees
1	16.34	20	1	60
2	16.34	20	1	45
3	16.34	0	0	60
4	16.34	0	0	45
5	65.37	20	0	60
6	65.37	20	0	45
7	65.37	0	1	60
8	65.37	0	1	45

Experimental Setup

All the tests were carried out on the Barite Sag Flow Loop (BSFL) available at the Tulsa University Drilling and Research Project (TUDRP). The schematic and the photo of the BSFL are shown in **Figure A1** and **A2** in the Appendix. The flow loop has a test section 12-feet long, consisting of a transparent outer casing with an inner diameter of 2'' and a drill pipe with an outer diameter of 1''. The drill pipe can be rotated up to 200 RPM. The eccentricity in this current work is either e = 0 for concentric drill pipe or e = 1 for fully eccentric drill pipe. The test section can be lifted with an inclination angle ranging from 30 to 90 degrees from vertical. The BSFL is designed to have no sag in the pipeline system. This means the accumulation of barite particles only occurs in the test section. The cross sectional area of the annulus of the test section is 2.356 in^2 and the maximum cross sectional area of the pipe system is 0.442 in^2. The ratio between the cross sectional area of the annulus and of the pipe system is 5:3. With this design, the average velocity in the pipe system is much higher than that in the annulus to prevent sag in the pipe system.

Oil-based drilling fluid provided by a major drilling fluids provider is used for these tests. API Barite was used to change the density of the fluid. The properties of the testing fluid are shown in **Table 2**.

Table 2: Properties of the testing fluid

Oil Water Ratio	Density lbm/gal	Yield point $lbf/100ft^2$	Consistency Index $lbfxs^n/100ft^2$	Flow behavior Index
80/20	12.20	4	0.5	0.68

As the drilling fluid was circulated, barite particles separated out of the suspension and accumulated at the lower side of the test section. This separation of barite particles resulted in a reduction in the circulating fluid density. Thus, the circulating density is a function of time and is monitored by a mass flow meter installed at the inlet of the test section. The measured circulating density at the inlet of the test section can be representative of the surface circulating density of drilling fluids during drilling operations. The temperature during the circulation also was recorded and used to adjust the measured densities to account for the effects of temperatures on densities. **Figures A3** and **A4** in the Appendix show the effect of temperature on the bulk density of the drilling fluid and the compensated density due to the temperature effect.

All the tests were conducted until the circulating density did not change. It took about 60 minutes for the circulating density to reach the equilibrium conditions for most of the tests. The difference in the circulating densities of the drilling fluid between the initial time and after 60 minutes is defined as the change in mud weight, ΔMW.

The test procedure is as follows:

1. Set the desired inclination angle and eccentricity.
2. Turn on the mixer and the heater to increase the temperature of the fluid up to 120°F.
3. Circulate the fluid through the pipe test section at the maximum flow rate of 26 GPM and start rotating the drill pipe at 100 RPM to remove the sediment bed back to the mud tank (about 10 - 15 minutes).
4. Stop the drill-pipe rotation and reduce the flow rate and pipe rotation to the desired values following the test matrix in Table 1.
5. Begin the computer program to record the circulating density, flow rate, and temperature of the fluid.
6. After 60 minutes, stop the program. Then subtract the initial circulating density (t = 0) from the circulating density at 60 minutes (equilibrium condition) to attain the change in mud weight ΔMW.

Experimental Results

The experimental data of Experiment 1 are given in Table 1 and are plotted and shown in **Figure 1**. The test was conducted at the annular velocity of 16.34 ft/minute, the pipe rotation of 20 RPM, fully eccentric dill pipe, and the inclination angle of 60 degrees. The results show the circulating density in lbm/gal and in kg/m^3 as a function of time in minute.

As described in the test procedure, the fluid was circulated at the maximum flow rate of 26 GPM (annular velocity of 212 ft/min or 3.54 ft/s) and the pipe rotation of 100 RPM to maintain a constant initial circulating density of 12.20 lbm/gal. When the annular velocity was reduced to 16.34 ft/min, and the pipe rotation reduced to 20 RPM, barite particles began to settle out of the suspension and form a bed at the lower side of the annulus. This accumulation of barite particles in the test section caused a reduction in the circulating density measured at the inlet of the test section.

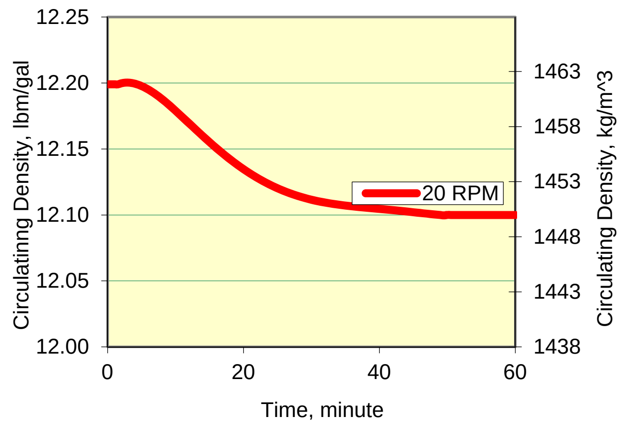

Figure 1: Circulating density vs. time
U_{ann} = 16.34 ft/min, e = 1, θ = 60^0, Pipe rotation = 20 RPM

Note that the magnitude of the reduction of the circulating density depends not only on the accumulation of barite particles in the test section but also on the total volume of the fluid tested. If the total volume of the tested fluid is small, the reduction in the circulating density will be high. The total volume of the tested fluid in this work was about 20 gallons and was maintained constant for all the tests. After 60 minutes of testing, the circulating density reaches an equilibrium value of 12.094 lbm/gal. Therefore, the change in mud weight at 60 minutes in comparision with the initial mud weight can be calculated as: ΔMW1 = 12.20 - 12.094 = 0.106 lbm/gal. This value is shown in the last column of Table 3.

The experimental data for Experiment 3 are shown in **Figure 2**. This experiment was carried out with an annular velocity of 16.34 ft/min, a drill-pipe rotation of 0 RPM, fully concentric drill-pipe, and an inclination angle of 60 degrees. The same drilling fluid as tested in Experiment 1 was circulated through the test section for 60 minutes. The circulating density measured at the inlet of the test section was recorded. The test procedure for Experiment 1 and Experiment 3 is exactly the same. All the drilling parameters are kept the same in the two experiments except the eccentricity and the pipe rotation. The experiment 1 is for fully eccentric drill-pipe and pipe rotation of 20 RPM; Experiment 3 is for fully concentric drill-pipe and 0 RPM pipe rotation. The change in mud weight after 60 minutes of testing for Experiment 3 was ΔMW3 = 0.061. This indicates that at low annular velocity of 16.34 ft/min, sag occurs in the fully concentric drill-pipe less than in the fully eccentric drill-pipe. The drill-pipe rotation of 20 RPM does not help much at this low annular velocity. Detail of discussions about effects of eccentricity and pipe rotation can be found in the work of Nguyen (January 2011).

The data shown in Figure 1 and Figure 2 are the average of the circulating densities from three runs, and hence the ΔMW1 and ΔMW3 are the average of three ΔMWs between the circulating densities at the initial time and at 60 minutes. Other experiments from Table 1 were conducted in the same procedure and similar to Experiments 1 and 3. The results in terms of ΔMW are shown in Table 3.

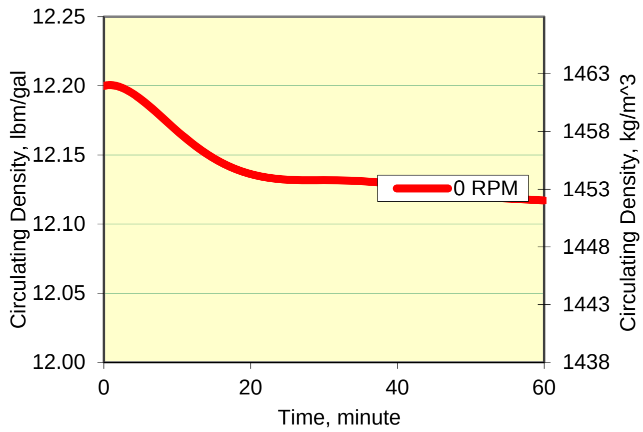

Figure 2: Circulating density vs. time
U_{ann} = 16.34 ft/min, e = 0, θ = 60^0, Pipe rotation = 20 RPM

Table 3: Experimental data from the BSFL. ΔMWs are the average circulating densities of three runs

Experiment Number	U_{ann} ft/min	RPM	e	θ	ΔMW lbm/gal
1	16.34	20	1	60	0.106
2	16.34	20	1	45	0.100
3	16.34	0	0	60	0.061
4	16.34	0	0	45	0.060
5	65.37	20	0	60	0.015
6	65.37	20	0	45	0.012
7	65.37	0	1	60	0.008
8	65.37	0	1	45	0.006

Comparison between Drilling Parameters on Barite Sag

As seen so far, the Taguchi method cannot evaluate and determine the effect of individual drilling parameters on barite sag. In order to quantitatively determine and compare the effects of annular velocity, pipe rotation, eccentricity and inclination angle on barite sag, the Analysis of Variance, ANOVA, was used to analyze the experimental data following the Taguchi experimental design given in Table 3.

ANOVA is a statistical method used to test for significant differences between two or more means by comparing variances. It is most commonly applied to the results of the experiment to determine the percent contribution of each factor. In this work, ANOVA can be used to obtain the percent contribution of each individual factor including annular velocity, pipe rotation, eccentricity, and inclination angle. The result from ANOVA helps to determine which of the drilling parameters need control and which do not.

The overall effect (combined effect) of annular velocity on barite sag is shown in **Figure 3**. This result is achieved from ANOVA with the input data based on Table 3. The y-axis represents the change in mud weight over 60 minutes, ΔMW, with the unit of lbm/gal. The x-axis is the annular velocity, which varies from 16.34 to 65.37 ft/min. As the annular velocity changes from 16.34 to 65.37 ft/min, the ΔMW changes from 0.0815 to 0.01 lbm/gal, which results in an "Effect" of 0.0815 – 0.01 = 0.0715 lbm/gal. This can be interpreted as follows: within the chosen levels of the drilling parameters (the pipe rotation in the range of 0 – 20 RPM, drill-pipe eccentricity of 0 – 1, inclination angle of 45 – 60 degrees) as the annular velocity increases from 16.34 to 65.37 ft/min, there is a reduction in sag of 0.0715 lbm/gal after 60 minutes of circulation in the testing flow loop. This is an indication of less sag occurring in the test section.

The ANOVA also outputs the percentage contribution, P. The P-value reports the significance of drilling parameters' levels. A small value of P indicates that there is a significant difference within the levels. Engineering normally uses a P-value of 0.05 as a small value. In this analysis, ANOVA gave a P-value of 0.000008 for the annular velocity. This P-value is much smaller than 0.05 and hence we can conclude that annular velocity has a significant impact on barite sag when changing the velocity from 16.34 to 65.37 ft/min.

The same analysis was carried out to study the overall effect of drill-pipe rotation, eccentricity, and inclination angle on barite sag shown in **Figures 4**, **5**, and **6**. The ANOVA results in an Effect of 0.0245, 0.018, and 0.003 lbm/gal for drill-pipe rotation, eccentricity and inclination angle, respectively. Therefore, within the chosen levels of the drilling parameters, changing the inclination angle from 45 to 60 degrees has the least impact on barite sag. In other words, the amount of sag will be similar when changing the inclination angle from 45 to 60 degrees. This finding tells us that when designing a well, we can vary the inclination angle from 45 – 60 degrees without concern about the sag difference.

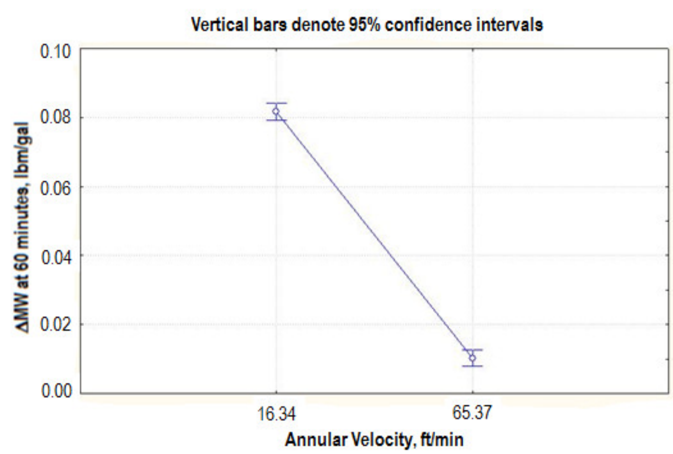

Figure 3: Overall effect of annular velocity

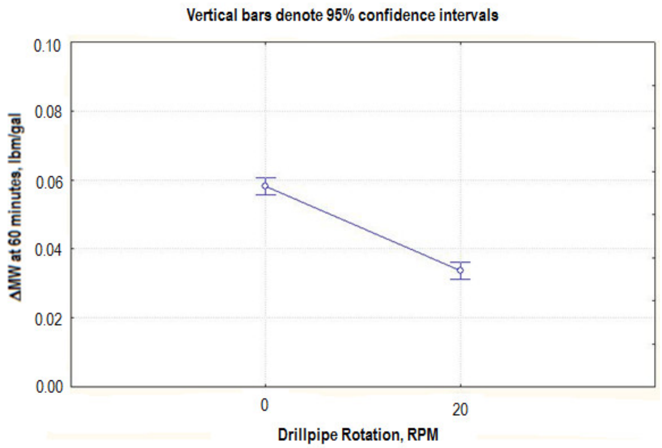

Figure 4: Overall effect of drill-pipe rotation

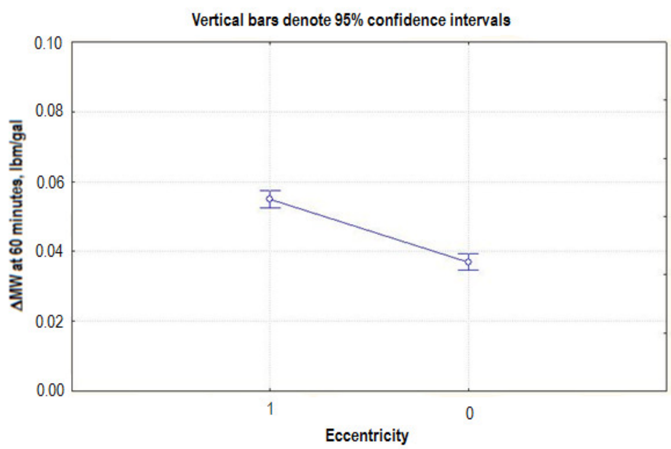

Figure 5: Overall effect of eccentricity

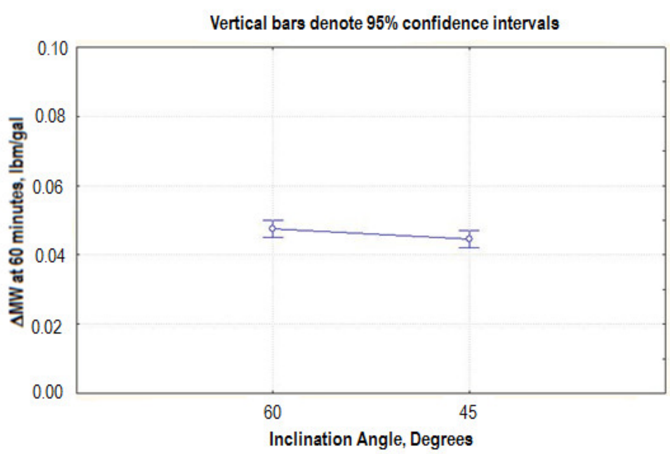

Figure 6: Overall effect of inclination angle

The results from ANOVA also gave the P-values of 0.000188, 0.000470, and 0.069137 for drill-pipe rotation, eccentricity, and inclination angle, respectively. The p-value of 0.069137, which is greater than 0.05, for the inclination angle indicates that there is not a significance when changing the inclination angle from 45 to 60 degrees. This result again supports the conclusion mentioned in the previous paragraph. The Effect and P-value for different drilling parameters is summarized in **Table 4**.

Table 4: Results from ANOVA analysis

Variables (Drilling parameters)	Effect lbm/gal	P
Annular Velocity	0.0715	0.000008
Drill-pipe Rotation	0.0245	0.000188
Eccentricity	0.0180	0.000470
Inclination Angle	0.0030	0.069137

The results from ANOVA can be used to quantitatively compare the individual effect of the drilling parameters on barite sag. The comparison between different impacts of each drilling parameter on barite sag shown in **Figure 6** was obtained from ANOVA analysis. The same results can be achieved by calculating the percentage of each Effect for each drilling parameter in Table 4. Within the chosen levels of the drilling parameters, the result clearly reveals that annular velocity has the most important impact and the inclination angle has minimal impact barite sag. The annular velocity contributes almost 60% in the prevention of barite sag. At the meantime, the inclination angle only contributes 2.5%. In other words, annular velocity should be the first priority factor considered to prevent barite sag. If it is possible, fluid should be circulated at as high a flow rate as possible.

Pipe rotation and eccentricity contributes almost 21% and 15%, respectively in preventing barite sag. These two factors have a smaller impact on preventing barite sag in comparison with the effect of the annular velocity. However, if the barite bed is compacted, sometimes it takes a long time to remove this bed by using only high annular velocity. In this case, drill-pipe rotation and high eccentric drill-pipe are very useful for removing the bed because they help to bring the bed back into suspension.

Further work on the bed pickup is needed in order to have a better understanding of the undesirable density fluctuations during drilling operations. Note that, the small effect of inclination angle on the change in mud weight is because the inclination angle is changed from 60 to 45 degrees. If the inclination angle changes from 60 to 90 degrees, the effect of the inclination angle will be more obvious.

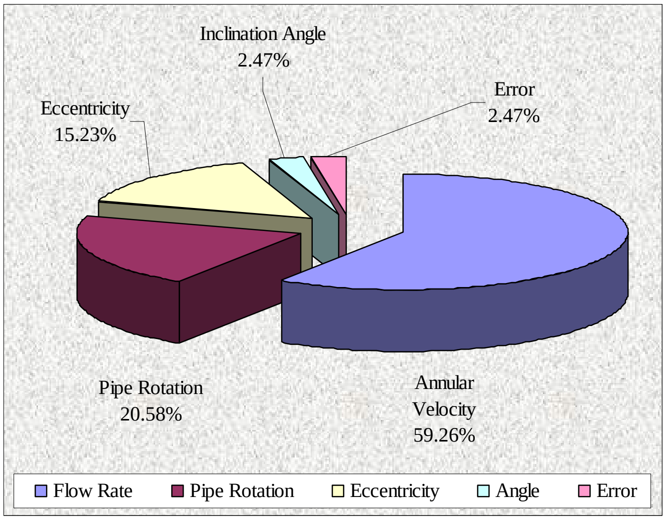

Figure 7: Individual effect of drilling parameters on barite sag

Summary and Conclusion

The Taguchi method was applied to design the experiments. Four drilling parameters including annular velocity, pipe rotation, eccentricity, and inclination angle were considered in this study. Each parameter has two levels as follows: 16.34 and 65.37 ft/min for annular velocity, 0 and 20 RPM for drill-pipe rotation, 0 and 1 for eccentricity, 45 and 60 degrees for inclination angle. With four drilling parameters and two levels for each parameter, the L8 orthogonal array was chosen according to the Taguchi method recommendation. The L8 orthogonal array tells us that eight experiments need to be conducted to completely understand the effect of each parameter on barite sag. Analysis of Variance (ANOVA), a statistical technique, was selected in this paper to analyze the experimental data. The following summary and concluding remarks can be drawn from this work:

1. The Taguchi method in conjunction with ANOVA can be used to quantitatively study the effect of drilling parameters on barite sag.
2. Annular velocity has the most significant impact on preventing barite sag. With the constraints of the drilling parameters in this work, annular velocity contributes up to 60% in terms of preventing sag in comparison with other drilling parameters. Therefore, annular velocity should be the first priority parameter considered to avoid barite sag.
3. Inclination angles in the range from 45 to 60 degrees have a very minimal effect on preventing barite sag. Sag will occur more or less similarly when changing the inclination angle in this range. Thus, when designing an oil/gas well, designers should not be concerned with the range of inclination angles from 45 to 60 degrees in terms of mitigating sag.
4. Drill-pipe rotation and eccentricity contribute 21% and 15%, respectively in preventing sag. This is about three times less impact on avoiding barite sag compared to the effect of the annular velocity. However, if a solid barite bed is formed, the drill-pipe rotation together with high eccentricity may significantly help to remove the barite bed.

Acknowledgements

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Nomenclature

ANOVA = *Analysis of variance*
API = *American Petroleum Institute*
BSFL = *Barite sag flow loop*
E = *Eccentricity*
F = *Fahrenheit*
ft = *feet*
G' = *Elastic modulus*
G'' = *Viscous modulus*
Gal = *gallon*
GPM = *Gallons per minute*
in = *inch*
lbm = *pound mass*
min = *minute*
P = *p-value – an output from ANOVA*
RPM = *Rotation per minute*
t = *time*
TUDRP = *Tulsa University Drilling and Research Project*
U = *Velocity*
U_{ann} = *Annular velocity*
ΔMW = *Change in mud weight between 0 and 60 minutes*
θ = *inclination angle*

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Appendix

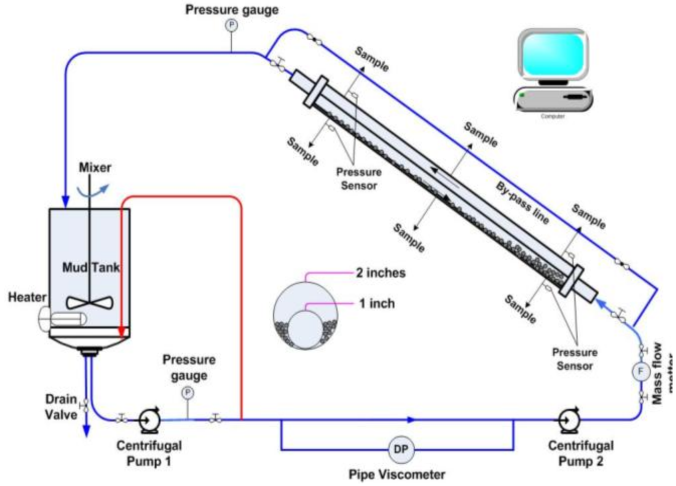

Figure A1: Schematic of the Barite Sag Flow Loop (BSFL)

Figure A2: Photo of the Barite Sag Flow Loop

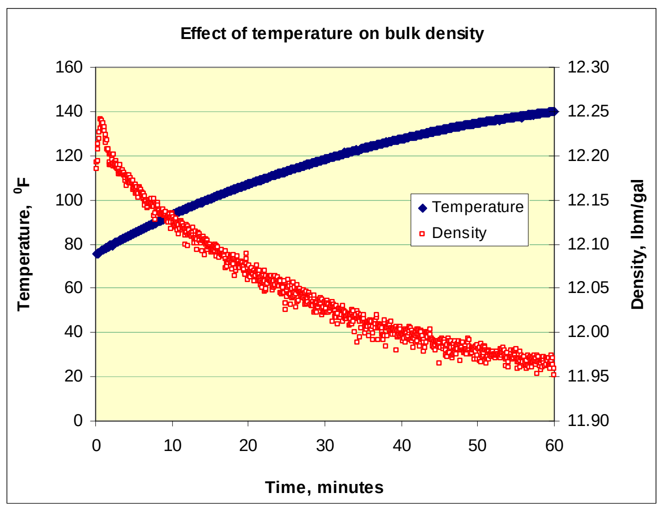

Figure A3: Effect of temperature on bulk density of oil-based drilling fluid

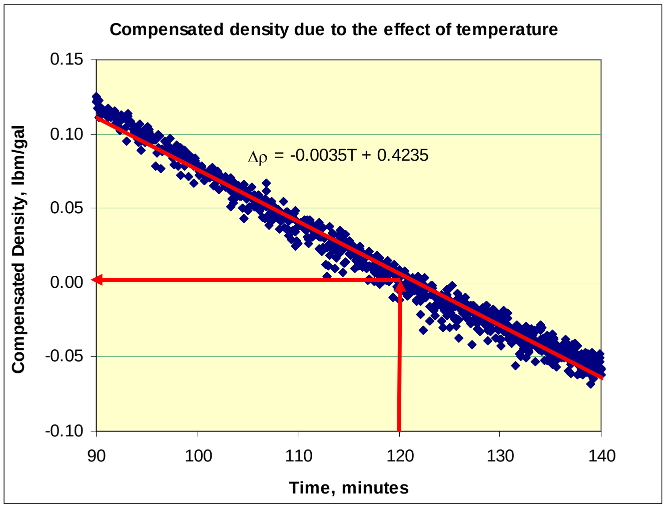

Figure A4: Compensated density due to the temperature effect